

## **Bay of Bengal Surface and Thermocline and the Arabian Sea**

Arnold L. Gordon  
Lamont-Doherty Earth Observatory  
61 Route 9W  
Palisades, NY 10964-8000  
tele: (845) 365-8325  
fax: (845) 365-8157  
[agordon@ldeo.columbia.edu](mailto:agordon@ldeo.columbia.edu)

Award Number: N00014-14-1-0065

### **LONG-TERM GOALS**

To quantify the processes that control freshwater exchanges within the Bay of Bengal and the interaction of the Bay of Bengal with the equatorial Indian Ocean, including linkage to the Arabian Sea and Indonesian Throughflow.

### **OBJECTIVES**

To investigate the ASIRI station and underway CTD and TSG underway data relationship the regional oceanography as resolved by the Argo profile and satellite data, as well as archived hydrographic stations, to identify the source region and associated trajectories of the meso-scale features; and to quantify thermohaline stratification and gradients along isopycnal surfaces and associated mixing, especially within the continental margins of the Bay of Bengal, and within the stream of salty thermocline water emanating from the Arabia Sea.

### **APPROACH**

The Bay of Bengal (BoB) is affected by many contrasting water types. The strong monsoonal forcing induces a complex array of energetic meso-scale and sub-meso-scales features. Both of these attributes complicate the view of regional oceanographic circulation. BoB is an 'oceanic estuary' exporting freshwater, largely of river origin, within the surface layer, compensated by saline water entering within the upper thermocline, derived mainly from the Arabian Sea. Identification of the export pathways (both eastern and western boundary paths are active at some time of the year) of the freshwater is blurred by the vigorous mesoscale. How BoB and the Arabian Sea interact with each other or with the zonally banded equatorial regimes, to form a quasi-steady state freshwater inventory is not clear. The Bay of Bengal receives much freshwater from rivers and precipitation; the Arabian Sea losses freshwater to the atmosphere. How low the SSS gets in the Bay of Bengal or how high in the Arabian Sea, depends on the oceanic exchanges between them via a ocean route immediately south of Sri Lanka, and with the equatorial ocean belt linked to these embayments along the eastern margin of Bay of Bengal and western margin of the Arabian Sea.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2014</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2014 to 00-00-2014</b>	
4. TITLE AND SUBTITLE <b>Bay of Bengal Surface and Thermocline and the Arabian Sea</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Lamont-Doherty Earth Observatory,61 Route 9W,Palisades,NY,10964-8000</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

BoB circulation and T/S stratification is investigated using the ASIRI CTD and underway CTD data, along with archive in situ, including the impressive Argo profile data since 2003, and satellite data. Argo data provide excellent coverage in the recent decade; relevant satellite data include SST, altimeter, ocean color and more recently the Sea surface salinity data acquired by the Aquarius satellite (launched in June 2011). I identify the likely origin of the waters within the eddy field, including the intra-thermocline eddy, to re-construct the regional circulation patterns. Streams of salty water spread into the Bay of Bengal in the upper thermocline, replacing surface export of low salinity water along the meridional boundaries, in an estuary-like set-up, the details of which change with season, and displace significant interannual variability.

## **WORK COMPLETED**

Argo data has been assembled to build a climatology (2003-2014) of the thermohaline stratification within the Bay of Bengal. This product is used to determine the regional origin of the T/S properties observed within the meso-scale during the 2013 ASIRI cruises, providing insight to the Bay of Bengal circulation and mixing processes.

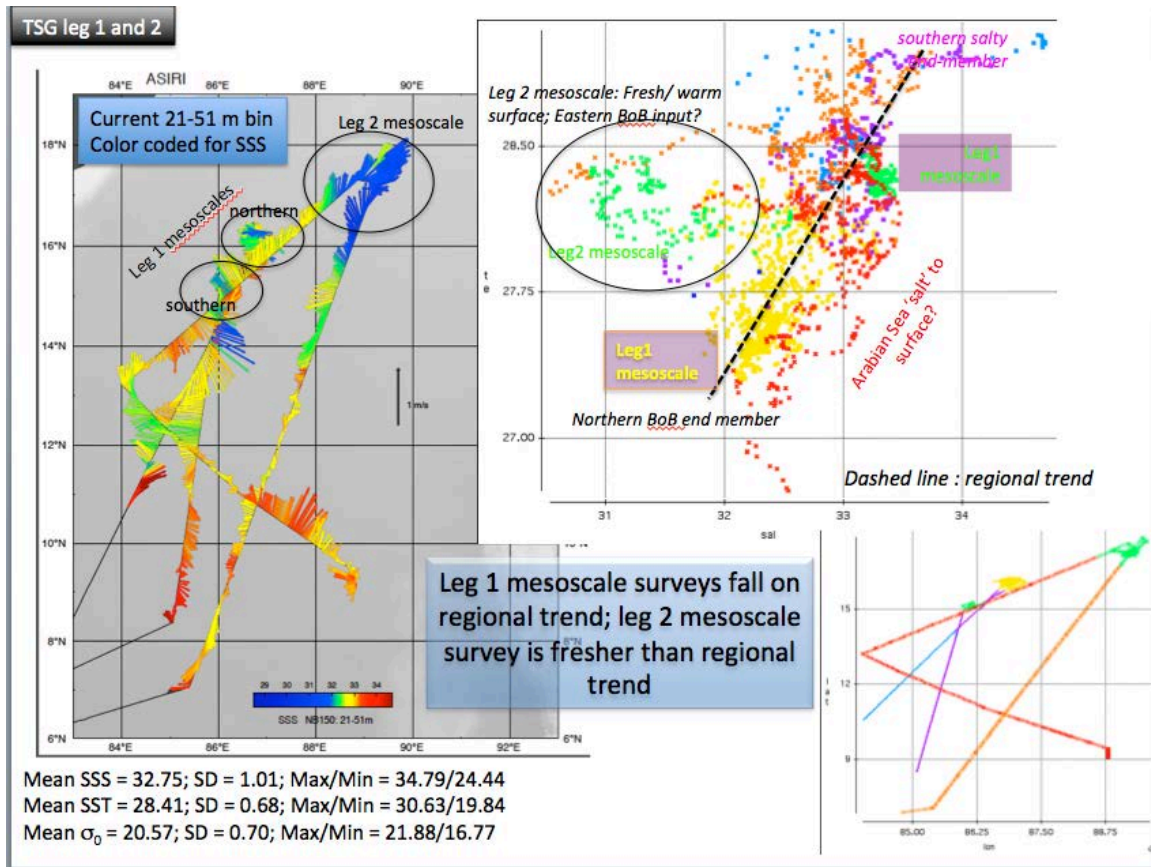
## **RESULTS**

Reported here are the initial results from the study of the relationship of the ASIRI CTD data set to larger, regional scale oceanography of the Bay of Bengal. The figure captions provide the basic descriptions that are not duplicated in the text. Seasonal climatology revealed by the Argo data set, has begun, but results too preliminary to present at this time.

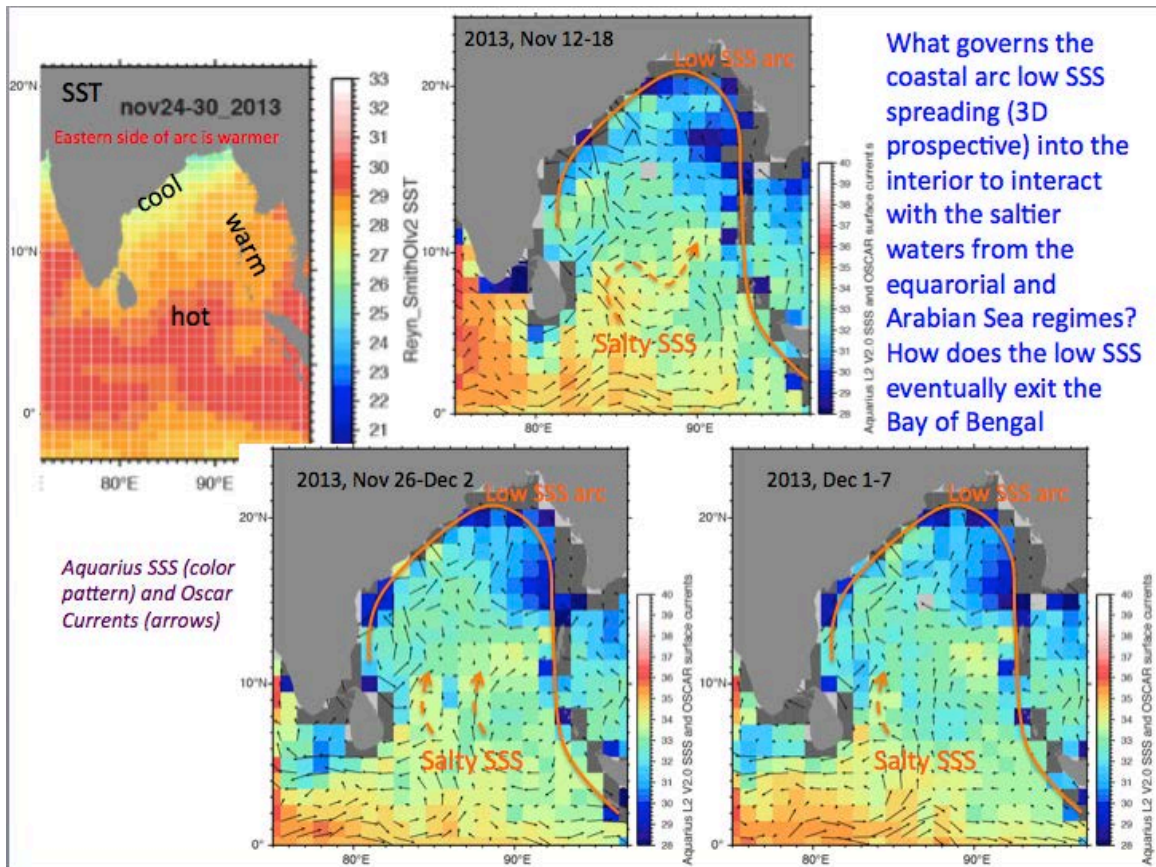
[A] Surface Water (reported at the March 2014 ASIRI meeting):

[B] Sections (reported at the March 2014 ASIRI meeting):

Argo profiles resolve the thermohaline stratification along the 'spine' of the Bay of Bengal (Figure 2). A salty feature is observed near 100 m, mainly in the summer monsoon that is derived from the Arabian Sea that enters the Bay of Bengal around the southern margin of Sri Lanka. This water is the primary salt input to compensate for the net freshwater input to the Bay of Bengal, mainly via river effluence from Southeast Asia. In the northern region, there is a cool/low salinity mass (Figure 1b), likely formed in winter (similar to the 'cold pool' of the NE coastal region of the US). This induced significant salinity gradient on isopycnals within the upper 100 m. Possible isopycnal spreading, likely associated by mesoscale processes, drive the cool low-salinity winter surface water of the margins into the interior of the Bay of Bengal, affecting regional vertical stratification of the upper thermocline with potential impact on the SST.



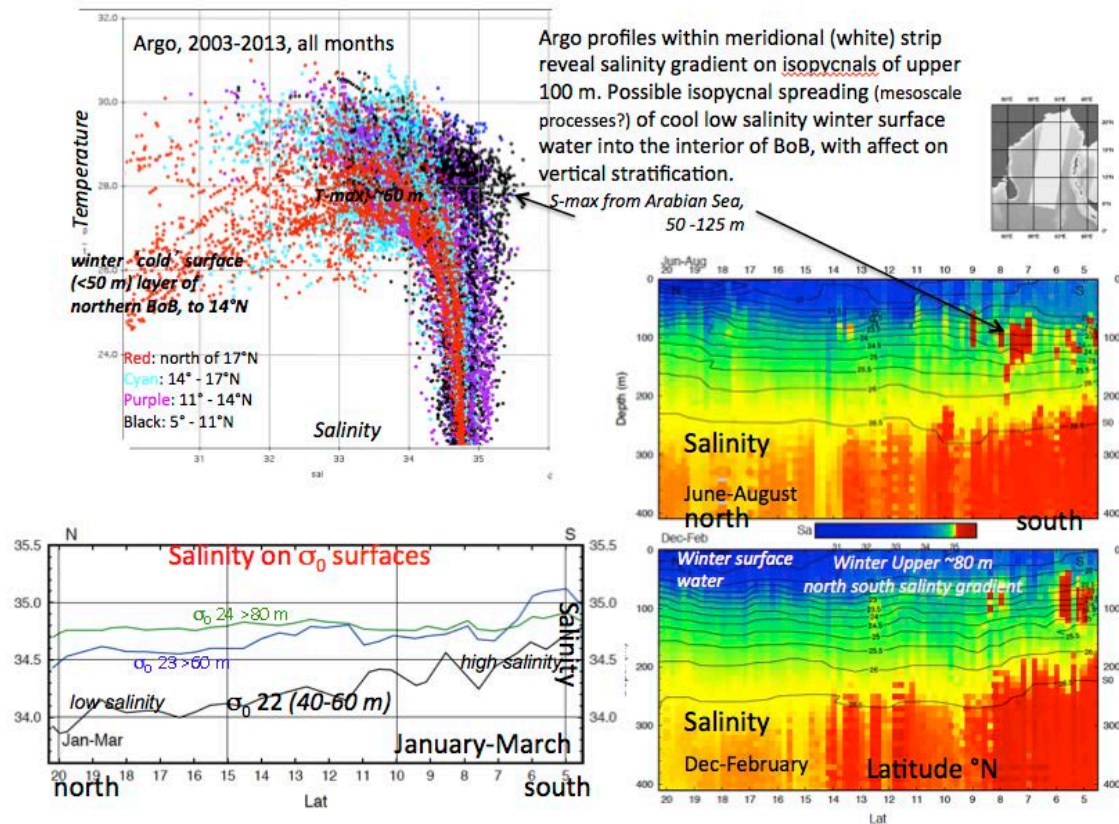
**Figure 1a: Sea surface temperature (SST) and salinity (SSS) relationship during ASIRI 2013 cruises. The left panel shows the hull ADCP vector, color-coded for SSS. The SST/SSS scatter falls along a line from the warm/salty southern regions to the cool/fresher northern margins. While the ASIRI leg 1 mesoscale surveys fall on the line, the ASIRI leg 2 mesoscale study falls well off the linear relationship, shifted toward lower SSS. It is proposed that the leg 2 mesoscale feature is derived from the eastern margin of the Bay of Bengal.**



**Figure 1b: Satellite based data of the Bay of Bengal SST and SSS in December 2013, time of the ASIRI cruises. The coastal arc of low SSS of varied SST somehow has to be exported from the Bay of Bengal embayment. The meridional axis of the central Bay of Bengal is relatively salty as needed to balance the river inflow.**

**The role of the meso-scale play in the heat/freshwater fluxes and how T/S properties spread on isopycnal surface and mix vertically, engaging the mixed layer and sea surface is a major goal of the ASIRI program.**



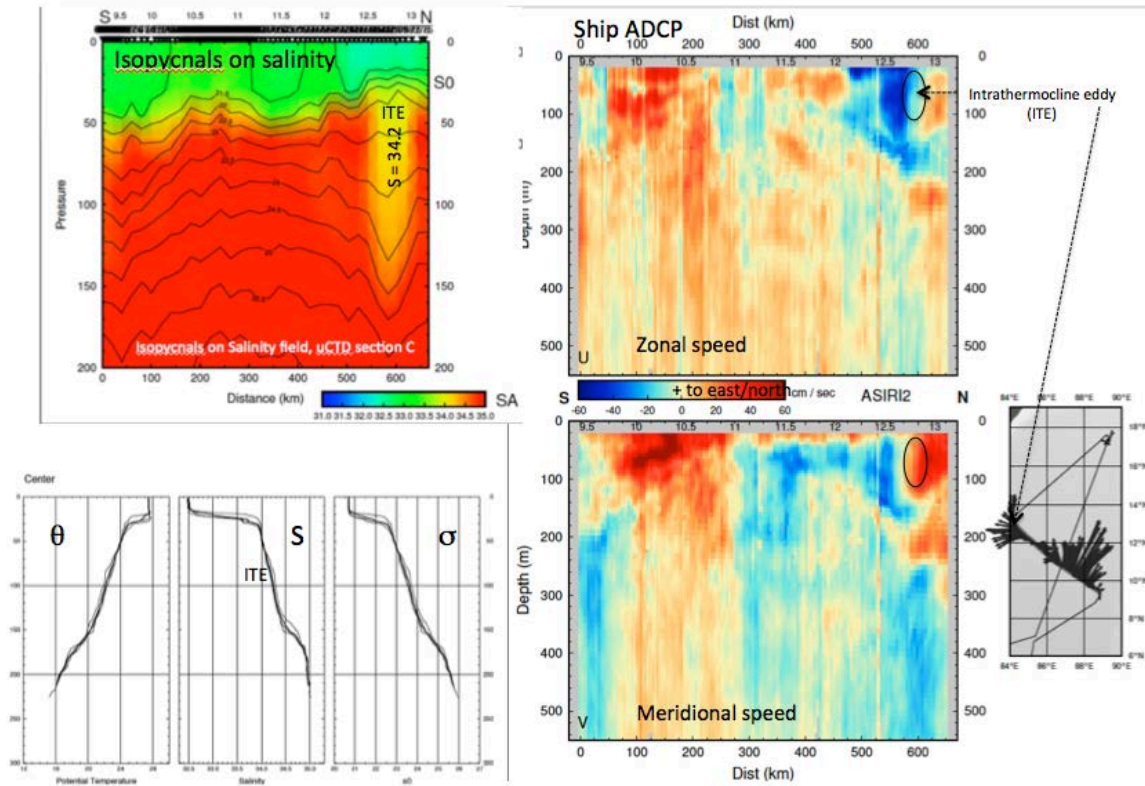


**Figure 2: Meridional Section: Argo profiles within meridional (white) strip (upper right panel) resolve the thermohaline stratification of the 'spine' of the Bay of Bengal. The lower right panels show the salinity field, black contours are isopycnals. The salinity gradient of the winter monsoon months on isopycnals of upper 100 m (lower left pane) reveal significant salinity variability along density surfaces.**

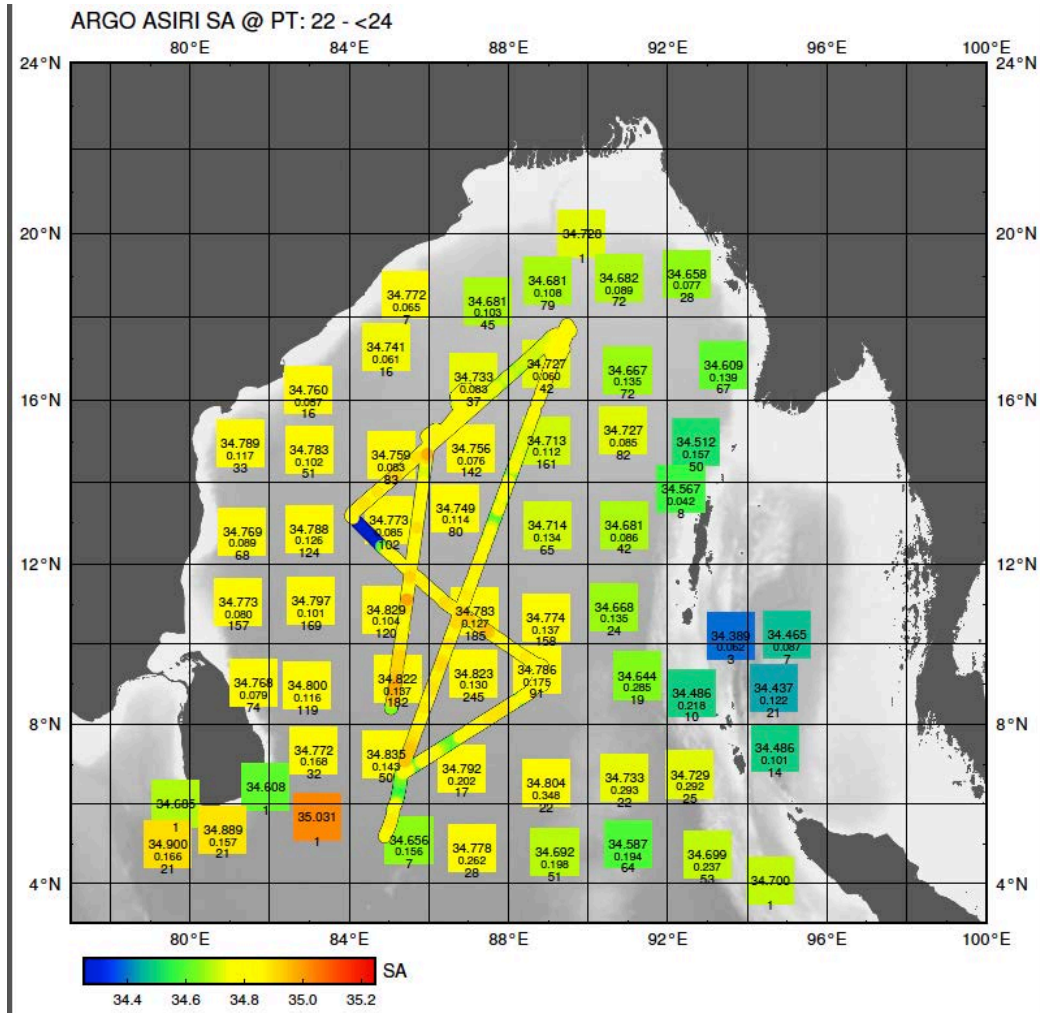
The intense spatial gradients are observed within sub-mesoscale and associated frontal structures. For example: ASIRI leg 2 stations 65 and 66, 20 km apart show 0.4 salinity differences on the 23 sigma-0 surface (~100 m depth). ASIRI stations 1 and 79, same lat/long, 12 days apart, reveal 0.5 differences in salinity from 22 to 25.5 sigma-0 50-200 m depth slab.

The zonal Argo section near 14°N (not shown here) reveals cool low salinity water, at the west and east margins, more so at the eastern boundary. This water may have advected from the northern BoB margin, preferentially along the eastern, Andaman margin. The salty stream from the Arabian Sea, within the thermocline, is found in the western side of the zonal section. This with the lower salinity surface water at the east, denote an anticyclonic circulation, at least in the winter monsoon months.

[C] Intrathermocline Eddy:



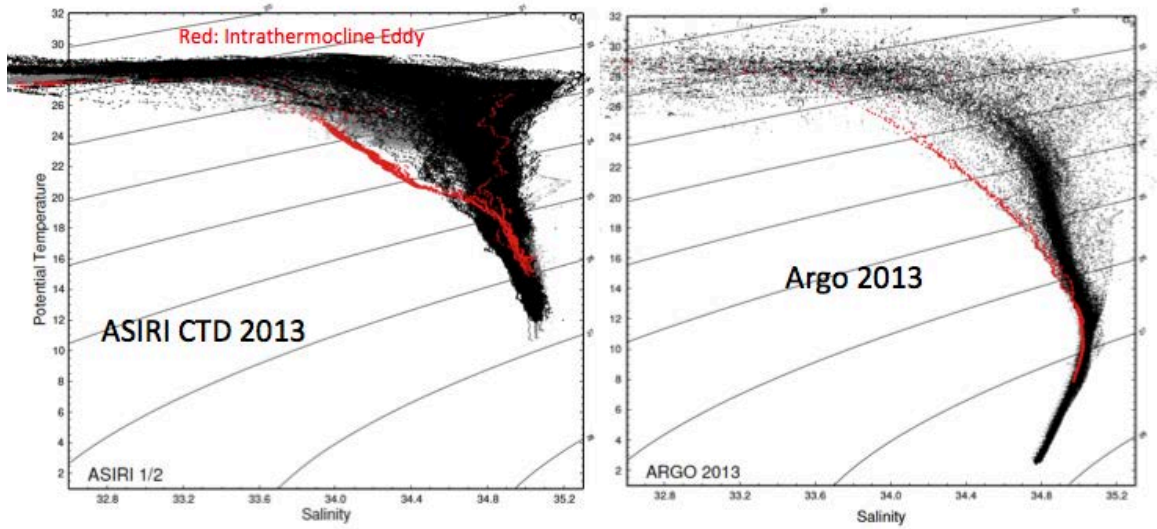
**Figure 3** During leg 2 the underway CTD reveals a strong intrathermocline eddy (ITE; left panels). A significant velocity field is associated with the displaced isopycnals (right panels). The geostrophic current relative to 200 m, marking the base of the ITE shows a maximum current of  $\sim 0.25$  m/sec at 70-80 meters depth. The surface current is about 50% of the subsurface  $v$ -max, so the ITE does have a surface expression in the velocity field (which is unlike ITE observed in the Japan Sea).



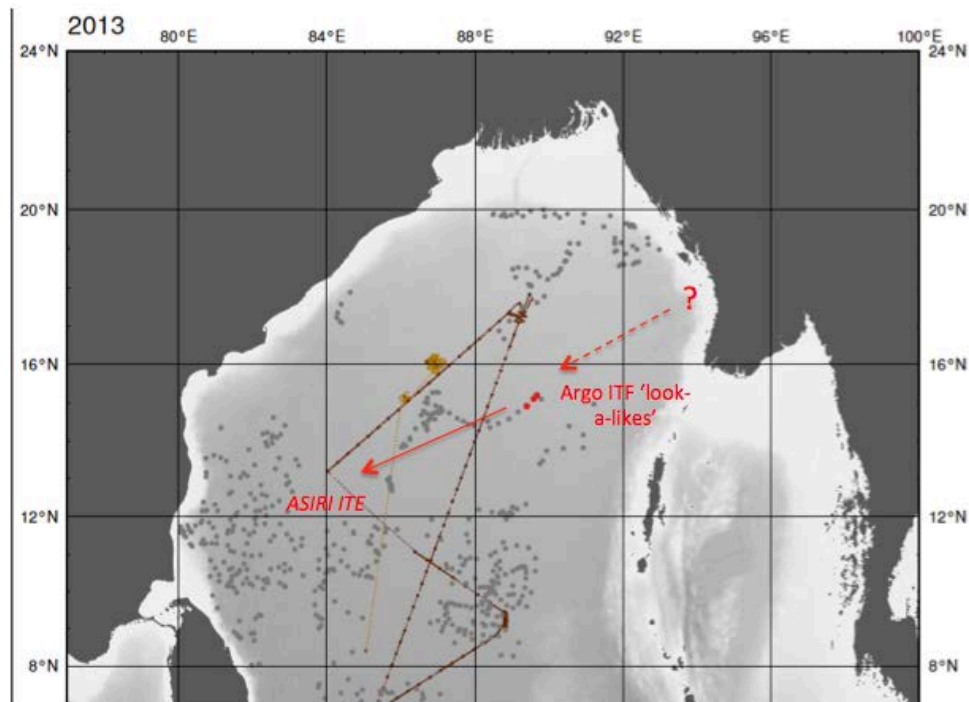
**Figure 4 ASIRI CTD salinity within the 22-24°C slab, superimposed over 2 x 2 lat/long boxes showing Argo mean salinity, SD, number of profiles; same salinity color code for ASIRI and the Argo climatology. Blue segment along ASIRI track marks the low salinity core of the Intrathermocline eddy (ITE).**

*The Argo climatology finds low salinity water within the 22-24°C slab [characteristic of the ITE core] can be found in the eastern boundary of the Bay of Bengal, which is the likely source of the ITE, consistent with the plots shown in figure 5.*



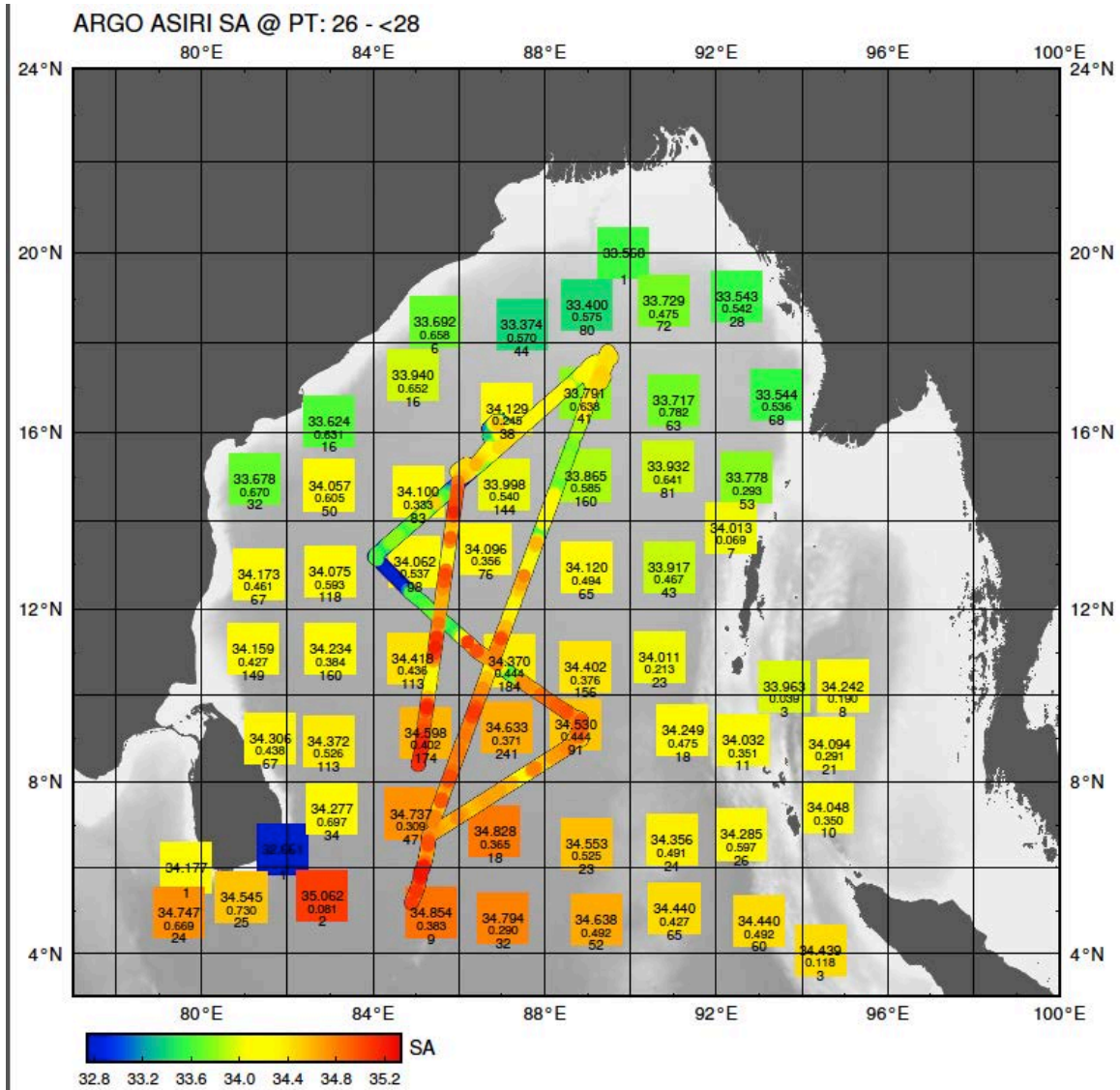


**Figure 5a** Left panel: The  $\theta/S$  from ASIRI leg 2; right panel: the Argo 2013  $\theta/S$ . The Intrathermocline Eddy (ITE) is shown in red.



**Figure 5b:** Map showing the ITE and Argo profiles best matching the ITE. Based on the Argo climatology, it is proposed that the water of the ITE core is derived from the eastern Bay of Bengal.

[D] Arabian Sea water within the Bay of Bengal:



**Figure 6: ASIRI CTD salinity within the 26-28°C, 70-90 m slab, superimposed over 2 x 2 lat/long boxes showing Argo mean salinity, SD, number of profiles; same salinity color code for ASIRI and the Argo climatology. The ASIRI track displays high salinity relative to the climatology 8 to 15°N along 86°E, suggesting a greater intrusion of the Arabian Sea upper thermocline water than depicted in the Argo climatology.**

[E] Other [briefly mentioned]: With Joaquim Goes (Lamont senior researcher) who is the first author, I am looking into an interannual signal of surface layer chl-a in the southwestern Bay of Bengal, that is related to the development of a cyclonic gyre near 12°N. We show that the gyre development is due to the blocking (by wind shift) of the export of western Bay of Bengal margin water around the southern rim of Sri Lanka into the Arabian Sea. It is noted that a +Indian Ocean Dipole event, occurs roughly 7 months later. The paper will soon be submitted to a journal. The abstract contains: ‘Here we report an atypical increase in phytoplankton biomass in the southwestern Bay of Bengal, whose regular occurrence prior to a positive IOD, hold promise as a simple, yet effective means of predicting an IOD event’.

## **IMPACT/APPLICATIONS**

The Bay of Bengal complex, energetic mesoscale and associated fronts play an essential (central) role in closing the regional scale heat and freshwater budgets both laterally and vertically, affecting the sea surface temperature and air-sea interaction and pycnocline structure.

## **RELATED PROJECTS**

## **HONORS/AWARDS/PRIZES**

Arnold L. Gordon Fellow, Association for the Advancement of American Science, February 2014